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Quantum Transistor Circuits: Physics of Semiconductor Light Sources

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6. AUTHOR(S)

Hyatt M. Gibbs and Galina Khitrova

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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13. ABSTRACT *(Maximum 200 words)*

The earlier research focused on destabilization (appearance of new frequencies, new polarizations, and/or new spatial patterns) and stabilization (locking of frequency, polarization, and pattern) by injecting a narrowband cw laser beam into a VCSEL. A very weak injected beam can have great effects because of cavity (>300) and gain (>10) enhancements. Not only were clean definitive data taken, but excellent agreement was also obtained between the data and plasma-theory computations. This new level of understanding and ability to model could be useful in locking arrays of VCSELs and stabilizing the frequency, polarization, and spatial pattern emitted by a VCSEL.

The more recent research has focused on the ***transfer of energy from a semiconductor to a light beam***. Work still in progress includes: observation of an order-of-magnitude shortening of the carrier lifetime for room-temperature carriers within a high-finesse microcavity compared with carriers at the same below-transparency density a few millimeters away in the same 100-nm bulk-GaAs layer, observation of very pronounced vacuum-field Rabi oscillations between a very narrow quantum-well exciton and a narrow microcavity mode, and 1.54-μm photoluminescence from Er^{3+} ions excited by energy transfer from optically excited InGaAs/GaAs quantum wells.

14. SUBJECT TERMS Semiconductor lasers. Vertical-cavity surface-emitting lasers. Injection patterns. Energy transfer. Phonon bottleneck. Cavity QED.

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TABLE OF CONTENTS

QUANTUM TRANSISTOR CIRCUITS:

PHYSICS OF SEMICONDUCTOR LIGHT SOURCES

HYATT M. GIBBS
and
GALINA KHITROVA

September 21, 1995

U.S. ARMY RESEARCH OFFICE

DAAL03-92-G-0329

OPTICAL SCIENCES CENTER
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FINAL TECHNICAL REPORT

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1. **ARO PROPOSAL NUMBER:** 30482-PH

2. **PERIOD COVERED BY REPORT:** 1 January 1995 - 19 July 1995

3. **TITLE OF PROPOSAL:** Injection Locking, Relaxation Oscillations, & Instabilities of Vertical-Cavity Surface-Emitting Lasers

4. **CONTRACT OR GRANT NUMBER:** DAAL03-92-G-0329

5. **NAME OF INSTITUTION:** University of Arizona

6. **AUTHORS OF REPORT:** Hyatt M. Gibbs and Galina Khitrova

7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:**

R. Jin, G. Khitrova, D. Boggavarapu, H.M. Gibbs, S.W. Koch, M.S. Tobin and R.P. Leavitt, "Physics of Semiconductor Vertical-Cavity Surface-Emitting Lasers," J. Nonlinear Opt. Phys & Matls. **4**, 141-161 (1995).

R. Jin, H.M. Gibbs, G. Khitrova, M.S. Tobin, R.P. Leavitt, D. Boggavarapu, F. Jahnke, and S.W. Koch, "Coulomb-Enhanced Decay of Carriers in Semiconductor Microcavities," Submitted to Phys. Rev. Lett.

G. Khitrova, "Quantum Wells at 2K and 12T: Test System for Phonon Bottlenecking and Quantum-Dot Lasing," Nonlinear Optical Materials and Applications '95, Cetraro, Italy, May 29-June 2, 1995, invited talk.

G. Khitrova, "Vortices and Transverse Mode Control in Vertical-Cavity Surface-Emitting Lasers," Laser Optics '95, St. Petersburg, Russia, June 27-July 1, invited talk.

G. Khitrova "Quantum Wells at 2K and 12T: Test System for Phonon Bottlenecking and Quantum-Dot Lasing," International Conference on Nonlinear Optical Physics and Applications, Harbin, China, July 25-31, 1995, invited talk SI-3.

H.M. Gibbs, "Coulomb-Enhanced Decay of Carriers in Semiconductor Microcavities," International Conference on Nonlinear Optical Physics and Applications, Harbin, China, July 25-31, 1995, invited talk SI-1.

H.M. Gibbs, "Carrier Decay and Lasing in Semiconductor Microcavities, "Army Research Lab., Adelphi, MD, May 17, 1995.

For a complete list of references, please see attached reports.

8. **SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:**

Hyatt M. Gibbs, Professor
Galina Khitrova, Assistant Professor
Jill Berger, Graduate Student
Ove Lyngnes, Graduate Student

9. **REPORT OF INVENTIONS (BY TITLE ONLY):** None

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FINAL TECHNICAL PROGRESS REPORT

Enhanced Spontaneous Emission of Carriers in Semiconductor Microcavities

Electron-hole pairs generated in less than 10 ps inside a high-finesse microcavity decay an order of magnitude faster than do carriers generated at the same below-transparency density a few millimeters away in the same layer of bulk GaAs but with the top mirror etched away; see Fig. 1. Cavity quantum electrodynamics (QED) continues to be a subject of intense research. In the regime of weak optical coupling, spontaneous emission can be modified by controlling the available modes into which emission can occur (modifying the photon density of states). With the advent of vertical-cavity surface-emitting lasers and monolithic dielectric-mirror very-high-finesse microcavities there has been much interest in controlling spontaneous emission of semiconductors to improve the directionality of light emitting diodes and lower the threshold of lasers. Early experiments measured enhancements as large as a factor of 2 in the emission rates of dye molecules and below-transparency-density quantum-well excitons (or carriers). None of these enhancements exceeded the well-known factor of 3 for a fixed dipole oriented parallel to and positioned at the center of an ideal half-wavelength metal-mirror planar cavity. Later calculations for the dielectric-mirror cavities used in those experiments predicted enhancements of only several percent for oriented atomic dipoles, i.e., much less than the factor of 2 observed. There has been no discussion of this discrepancy much less theory explaining it in the literature to our knowledge. Meanwhile there have been two experiments, using Er^{3+} ions implanted in SiO_2 and low-density quantum-well excitons, which are described quantitatively by atomic-dipole controlled spontaneous emission theory. In contrast, our experiments over the last four years show an order of magnitude enhanced spontaneous emission rate for room-temperature below-transparency-density bulk-GaAs carriers. The physics of this much larger cavity QED effect, just under conditions of greatest technological importance, turns out to be relatively simple as extracted from fully quantum-mechanical many-body semiconductor theory and many long computer runs. The well-known very large (much greater than 3) enhancement for those emitters able to emit into the cavity mode is not almost cancelled by strong inhibition of all other emitters (as in the fixed-dipole case). This is because Coulomb scattering makes it a near certainty that each electron-hole pair whatever its initial wavevector will have the fast-decaying wavevector within its lifetime. We have the first agreement between experimental data and a theory for enhanced spontaneous emission that exceeds the atomic-dipole upper limit of 3. A modification of the present theory slowing down Coulomb scattering appropriately for lower dimensional quantum wells may eventually resolve the aforementioned discrepancy there as well.

Quantum-Dot Versus Quantum-Well Vertical-Cavity Surface-Emitting Lasers

We have designed and grown two VCSELs for 2K operation using three 5.5-nm InGaAs/GaAs quantum wells (919 nm exciton peak) in the center of a 1λ GaAs spacer that lase around 920 nm when pumped at 826 nm cw. Using a photodiode/sampling scope with 40-ps time resolution, we have found no increase in the delay between 100-fs Ti:S excitation and VCSEL lasing with the application of a 12T magnetic field (it is necessary

to scan to a new spot on the sample to bring the gain and cavity mode back into coincidence). We conclude that *there is no phonon bottleneck effect* since cw lasing occurs and there is no increase in delay for pulsed operation. Any change in lasing threshold as a result of the narrowing of the density of states is so small that very careful measurements will be needed to quantify it. Recently we have grown VCSELs with very narrow (1 meV = 0.6 nm) quantum-well linewidths that exhibit very pronounced vacuum-field Rabi splitting and should be ideal for quantum-dot/quantum-well comparisons.

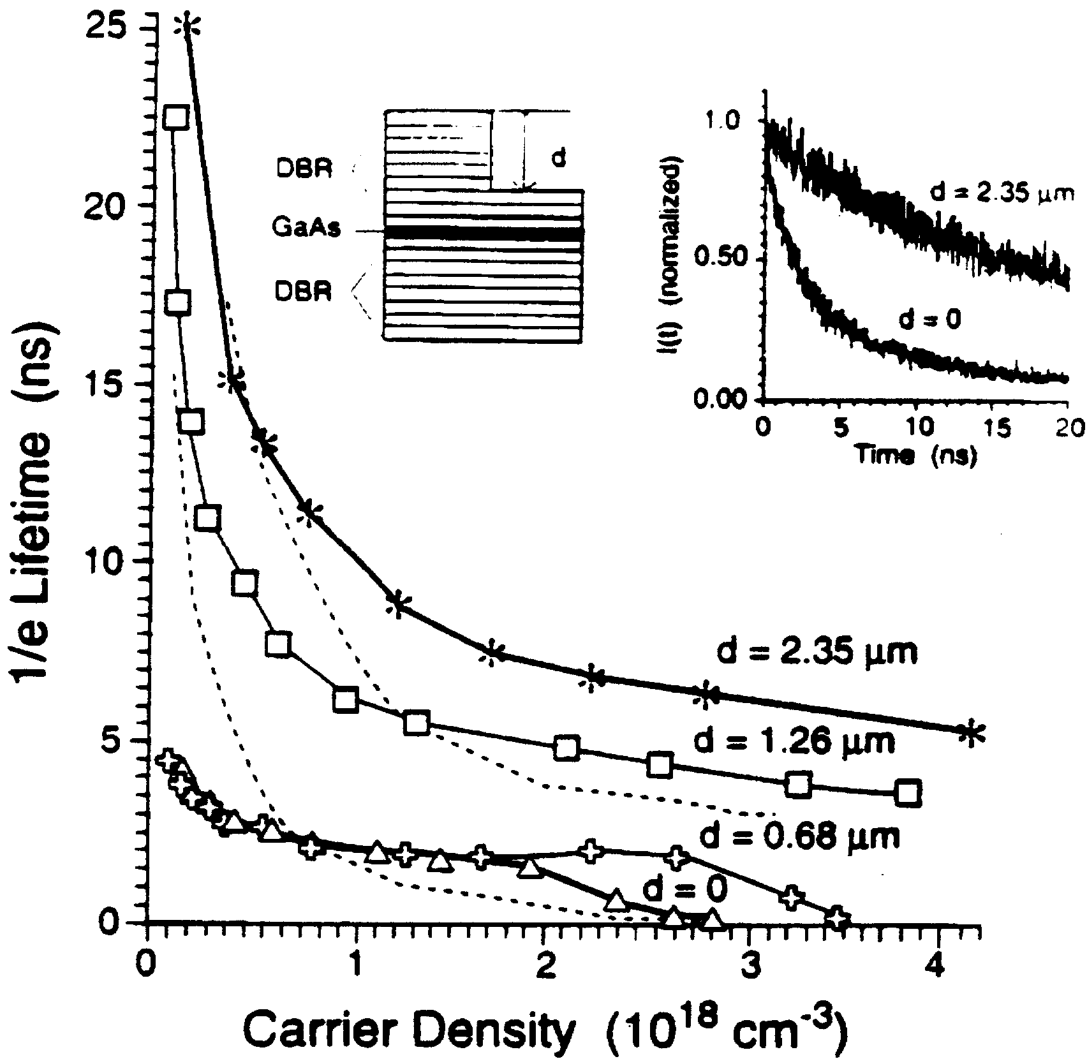


Fig. 1. Measured photoluminescence lifetimes of carriers in a 100-nm GaAs layer in the center of microcavities with a portion d of the 2.94-µm mirror etched away. The dashed curves are for a microcavity before and after etching away the substrate and all but six periods of the bottom mirror. The inset shows decays for the lowest carrier density.

PHYSICS OF SEMICONDUCTOR LIGHT SOURCES

OBJECTIVE

TO OBSERVE AND UNDERSTAND THE PHYSICS OF PHENOMENA WHICH TRANSFER ENERGY FROM AN EXCITED SEMICONDUCTOR TO A LIGHT BEAM.

APPROACH

TO GROW MATERIALS AND FABRY-PEROT STRUCTURES BY MBE AND TO STUDY THEM BY CW AND ULTRAFAST LASER TECHNIQUES.

STATUS/ACCOMPLISHMENTS

Start Date
1 JULY 1992

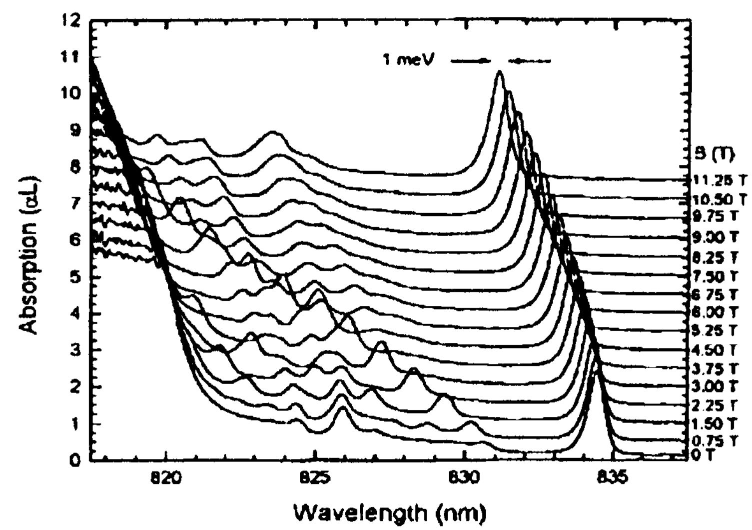
Program Duration
36 months

3 KEY OVERALL MILESTONES

SPATIAL SOLITONS IN A SEMICONDUCTOR AMPLIFIER, Phys. Rev. Lett. **70**, 920 (1993)

ACCELERATION OF COHERENT TRANSFER OF ENERGY BY STIMULATED EMISSION AND ABSORPTION, Phys. Rev. Lett. **71**, 1534 (1993)

THRESHOLDLESS "LASERS" ARE ONLY LEDs, Phys. Rev. A **49**, 4038 (1994)



Subjecting 20 InGaAs/GaAs quantum wells to a magnetic field of 12T results in a well-isolated magneto exciton absorption, with near-ideal quantum-dot properties.

SC

'94-'95 TECHNICAL ACCOMPLISHMENTS

- ***Magnetoexciton Quantum Dots***

  InGaAs/GaAs quantum wells with very narrow absorption (1 meV) grown by MBE. Quantum well magnetoexciton is "quantum dot" with well-isolated lowest-energy transition.

- ***Phonon Bottleneck***

  CW lasing of quantum-well magnetoexciton "quantum dot" VCSEL. CW lasing and delay in lasing following fs excitation show no phonon bottleneck problem.

- ***Vacuum-Field Rabi Splitting***

  Normal-mode coupling between microcavity and quantum-well magnetoexciton with record splitting to linewidth ratio.

- ***Enhanced Spontaneous Emission***

  Explanation of the accelerated decay of room-temperature below-transparency-density carriers in a microcavity.

- ***Erbium-Doped Semiconductor Light Sources***

  Photoluminescence from Er^{3+} in InGaAs/GaAs quantum well.

ARPA/ARO

SC

TECHNOLOGY TRANSITION/INSERTION PLAN

CONTINUE CHOOSING SEMICONDUCTOR PHYSICS PROBLEMS RELEVANT TO ARPA, DISCUSSING THEM WITH OTHER ARPA CONTRACTORS AT THE ARPA REVIEW AND OTHER MEETINGS, AND PUBLISHING RESULTS IN REFEREED JOURNALS

INDUSTRIAL CONTACTS

Dr. N.K. Dutta
AT&T Bell Labs

Dr. W. Ishak
Hewlett-Packard

Improving III - V VCSELs and LEDs

Dr. J. Lam
Hughes Research Labs

Erbium-doped semiconductor light sources

Member companies of the Arizona/Maryland NSF Cooperative Research Center entitled: **Center for Optoelectronic Devices, Interconnects, and Packaging (COEDIP)**

ARMY RESEARCH LABORATORY COLLABORATORS

R. Jin, R.P. Leavitt, M.S. Tobin, G.J. Simonis

ADDENDUM A

TECHNICAL PROGRESS REPORT

FOR PERIOD

1 JAUNARY 1994 - 31 DECEMBER 1994

TECHNICAL PROGRESS REPORT

FIFTEEN COPIES REQUIRED

1. **ARO PROPOSAL NUMBER:** 30482-PH

2. **PERIOD COVERED BY REPORT:** 1 January 1994 - 31 December 1994

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5. **NAME OF INSTITUTION:** University of Arizona

6. **AUTHORS OF REPORT:** Hyatt M. Gibbs and Galina Khitrova

7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:**

R. Jin, D. Boggavarapu, M. Sargent III, P. Meystre, H. M. Gibbs, and G. Khitrova, "Photon-Number Correlations Near the Threshold of a Microcavity Laser," Phys. Rev. A **49**, 4038 (1994).

H. M. Gibbs, review of *Optics of Semiconductor Nanostructures*, edited by F. Henneberger, S. Schmitt-Rink, and E. O. Gobel (Akademie Verlag, Berlin, 1993), Opt. Matls. (1994).

F. Brown de Colstoun, A. V. Fedorov, G. Khitrova, T. R. Nelson, C. W. Lowry, H. M. Gibbs, T. M. Brennan, and B. G. Hammons, "Gaussian-Beam-Induced Vortices in Vertical-Cavity Surface-Emitting Lasers," IQEC '94.

H. M. Gibbs, "VCSEL's, ARM's, and NLDC's," Second Technion Symposium on Optoelectronics, April 2-4, 1994, Haifa, Israel. Invited talk.

H. M. Gibbs, "Surface-Emitting Laser with Injection: Instabilities, Locking, Accelerated Energy Transfer, and Vortices," 185-188, Nanostrucutres: Physics and Technology, International Symposium (St. Petersburg, Russia, June 20-24, 1994).

R. Jin, M. S. Tobin, R. P. Leavitt, G. J. Simonis, H. M. Gibbs, G. Khitrova, D. Boggavarapu, and S. W. Koch, "Observation of Enhanced Carrier Decay Rate in a Semiconductor Microcavity Laser," M225, OSA'94.

H. M. Gibbs, G. Khitrova, C.W. Lowry, and S. W. Koch, "Acceleration of Coherent Transfer of Energy by Stimulated Emission and Absorption," Opt. and Phot. News 14 (Dec. 1994).

R. Jin, G. Khitrova, D. Boggavarapu, H. M. Gibbs S. W. Koch, M. S. Tobin, and R. P. Leavitt, "Physics of Semiconductor Vertical-Cavity Surface-Emitting Lasers," J. Nonlin. Opt. Phys. and Appl. Invited paper accepted for Jan '95 special issue.

O. Lyngnes, H. M. Gibbs, G. Khitrova, J. D. Berger, T. R. Nelson, Jr., and V. Zapasskii, "A Vertical Cavity Surface Emitting Laser Operating in a 12T Magnetic Field at 2K Temperature," Quantum Optoel. Top. Mtg., Mar 13-17, 1995.

F. Brown de Colstoun, G. Khitrova, A. V. Federov, T. R. Nelson, C. Lowry, T. M. Brennan, B. G. Hammons, and P. D. Maker, "Transverse Modes, Vortices, and Vertical-Cavity Surface-Emitting Lasers," Chaos, Solitions, and Fractals, **4**, 1575-1596 (1994).

G. Khitrova, "Coherent Energy Transfer in Microcavity Lasers," MF2, ILS'94. Invited talk.

G. Khitrova, "Acceleration of Coherent Transfer of Energy by Stimulated Emission and Absorption," LEOS'94. Invited talk.

N. Peyghambarian, S. G. Lee, R. Jin, J. Yumoto, G. Khitrova, H. M. Gibbs., R. Binder, and S. Koch, "Femtosecond Switching Speed in a Current-Injected GaAs/AlGaAs Multiple-Quantum-Well Nonlinear Directional Coupler," Opts and Phot. News, 40 (Dec 1994).

S. G. Lee, R. Jin, B. P. McGinnis, J. Yumoto, G. Khitrova, H. M. Gibbs, S. W. Koch, and N. Peyghambarian, "Subpicosecond Switching in a Current Injected GaAs/AlGaAs Multiple-Quantum-Well Nonlinear Directional Coupler," Appl. Phys. Lett. **64**, 454-456 (1994).

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Hyatt M. Gibbs, Professor
Galina Khitrova, Assistant Professor
Deepak Boggavarapu, Post-doc
Jill Berger, Graduate Student
Eric Lindmark, Graduate Student

9. REPORT OF INVENTIONS (BY TITLE ONLY): None

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ADDENDUM B

TECHNICAL PROGRESS REPORT

FOR PERIOD

1 JAUNARY 1993 - 31 DECEMBER 1993

ADDENDUM C

TECHNICAL PROGRESS REPORT

FOR PERIOD

1 JULY 1992 - 31 DECEMBER 1992

PROGRESS REPORT

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7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:**

Reviewed journal publications with ARPA and/or ARO acknowledgement:

1. C. W. Lowry, F. Brown de Colstoun, A. E. Paul, G. Khitrova, H. M. Gibbs, J. W. Grantham, R. Jin, D. Boggavarapu, S. W. Koch, M. Sargent III, T. M. Brennan, and B. E. Hammons, "Acceleration of Coherent Transfer of Energy by Stimulated Emission and Absorption," Phys. Rev. Lett. **71**, 1534 (1993).
2. D. Boggavarapu, R. Jin, J. W. Grantham, Y. Hu, F. Brown de Colstoun, C. W. Lowry, G. Khitrova, S. W. Koch, M. Sargent III, H. M. Gibbs, and W. Chow, "Instabilities of a Microcavity Laser with Weak Injected Signal," Opt. Lett. **18**, 1846 (1993).
3. R. Jin, D. Boggavarapu, M. Sargent III, P. Meystre, H. M. Gibbs, and G. Khitrova, "Photon-Number Correlations Near the Threshold of a Microcavity Laser," submitted to Phys. Rev. A.
4. F. Jahnke, S. W. Koch, and K. Henneberger, "Dynamic Response of Short-Cavity Semiconductor Lasers," Appl. Phys. Lett. **62**, 2313 (1993).
5. F. Jahnke and S. W. Koch, "Theory of Carrier Heating through Injection Pumping and Lasing in Semiconductor Microcavity Lasers," Opt. Lett. **18**, 1438 (1993).
6. M. F. Pereira, S. W. Koch, and W. W. Chow, "Effects of Strain and Coulomb Interaction on Gain and Refractive Index in Quantum Well Lasers," JOSA B **10**, 765 (1993).

Publications continued on next page

8. **SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:**

Professors: H. Gibbs, G. Khitrova, and S. Koch
Asst. Res. Prof: R. Jin
Postdoctoral Fellows: F. Jahnke and Y. Hu
Students: C. W. Lowry (PhD, May 93), D. Boggavarapu (PhD, Aug. 93), F. Brown de Colstoun, J. Berger, and R. Boye

9. **REPORT OF INVENTIONS (BY TITLE ONLY):** None

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Tucson, AZ 85721

Publications continued:

Meeting proceedings and talks:

7. C. W. Lowry, F. Brown de Colstoun, G. Khitrova, H. M. Gibbs, A. W.Paul, S. W. Koch, T. M. Brennan and B. E. Hammons, "Asymmetric Gain and Intermodal Asymmetry Transfer in a Vertical-Cavity Surface-Emitting Laser," QTuK5, QELS '93.
8. H. M. Gibbs, "Acceleration of Coherent Transfer of Energy by Stimulated Emission and Absorption in a Vertical-Cavity Surface-Emitting Laser," Laser Optics '93, St. Petersburg, June 21-25, 1993, Plenary Talk; Proceedings paper: C. W. Lowry, G. Khitrova, F. Brown de Colstoun, A. E. Paul, H. M. Gibbs, J. W. Grantham, R. Jin, D. Boggavarapu, S. W. Koch, M. Sargent III, T. M. Brennan, and B. E. Hammons, "Power Broadening of Coherent Energy Transfer in Semiconductor Gain Media."
9. H. M. Gibbs, G. Khitrova, C. W. Lowry, D. Boggavarapu, F. Brown de Colstoun, R. Jin, J. W. Grantham, A. E. Paul, Y. Hu, S. W. Koch, M. Sargent, T. M. Brennan, and B. E. Hammons, "VCSELs with Injection: Instabilities and Local Gain Modification," CSNO '93, Invited Talk; Proceedings paper: C. W. Lowry, H. M. Gibbs, G. Khitrova, D. Boggavarapu, F. Brown de Colstoun, R. Jin, J. W. Grantham, A. E. Paul, Y. Hu, S. W. Koch, M. Sargent, T. M. Brennan, and B. E. Hammons, "Injection Induced Instabilities and Local Gain Modification in VCSELs."
10. G. Khitrova, C. W. Lowry, F. Brown de Colstoun, A. E. Paul, H. M. Gibbs, J. W. Grantham, R. Jin, D. Boggavarapu, S. W. Koch, M. Sargent III, T. M. Brennan, and B. E. Hammons, "Acceleration of Coherent Transfer of Energy by Stimulated Emission and Absorption," International Conference on Nonlinear Optics and Physical Applications (ICNOPA '93), Nanjing, PRC, Sept. 6-10, Invited Talk.
11. F. Brown de Colstoun, C. W. Lowry, G. Khitrova, H. M. Gibbs, A. E. Paul, S. W. Koch, T. M. Brennan and B. E. Hammons, "Asymmetric Gain in a Vertical-Cavity Surface-Emitting Laser," Topical Meeting on Quantum Optoelectronics.
12. H. M. Gibbs, "Nonlinear Optics of Semiconductor Heterostructures," International Topical Conference on Research Trends in Nonlinear and Quantum Optics, La Jolla, Nov. 22-24, 1993, Invited Talk.
13. H. M. Gibbs, R. Jin, D. Boggavarapu, M. Sargent III, P. Meystre, and G. Khitrova, "Photon-Number Correlations Near the Threshold of Microcavity Lasers," ICNOPA '93, Invited Talk.
14. R. Jin, D. Boggavarapu, M. Sargent III, P. Meystre, H. M. Gibbs and G. Khitrova, "Photon-Number Correlations in a Microcavity Laser," APS March Meeting.
15. G. Khitrova, F. Brown de Colstoun, C. W. Lowry, E. M. Wright, H. M. Gibbs, T. M. Brennan, and B. E. Hammons, "Spatial Patterns in Semiconductor Lasers," LEOS '93, invited talk.
16. G. Khitrova, "Spatial Patterns in Nonlinear Optics," International Symposium on Polymers POLYMEX-93, Nov. 1-5, 1993, Cancun, Mexico, invited talk.
17. F. Brown de Colstoun, A. V. Fedorov, G. Khitrova, T. R. Nelson, C. W. Lowry, H. M. Gibbs, T. M. Brennan, and B. G. Hammons, "Gaussian-Beam-Induced Vortices in Vertical-Cavity Surface-Emitting Lasers," submitted to IQEC '94.

PROGRESS REPORT

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7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:**

    1. R. Jin, D. Boggavarapu, G. Khitrova, H. M. Gibbs, Y. Z. Hu, S. W. Koch, and N. Peyghambarian, "Linewidth Broadening Factor of a Microcavity Semiconductor Laser," Appl. Phys. Lett. **61**, 1883 (1992).

    2. R. Jin, D. Boggavarapu, M. Sargent III, P. Meystre, H. M. Gibbs, and G. Khitrova, "Photon-Number Correlations Near the Threshold of a Microcavity Laser," submitted to Phys. Rev. Lett.

    3. H. M. Rose, M. Lindberg, W. Chow, S. W. Koch, and M. Sargent, "Composite-Cavity-Mode Approach to Single-Mode Semiconductor-Laser Feedback Instabilities," Phys. Rev. A **46**, 603 (1992).

    4. W. W. Chow, M. Pereira, and S. W. Koch, "Many-Body Treatment of the Modulation Response in a Strained Quantum Well Semiconductor Laser Medium," Appl. Phys. Lett. **61**, 758 (1992).

    5. F. Jahnke, S. W. Koch, and K. Henneberger, "Dynamic Response of Short Cavity Semiconductor Lasers," submitted to Appl. Phys. Lett.

8. **SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:**

    H. Gibbs, G. Khitrova, S. Koch
    D. Boggavarapu
    R. Jin

9. **REPORT OF INVENTIONS (BY TITLE ONLY):** None

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